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Creep characteristics of thin prestressed concrete slabs

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CREEP CHARACTERISTICS

OF

THIN PRESTRESSED CONCRETE SLABS

BY

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A

THESIS

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INTRODUCTION

Prestressed concrete as a structural material is finding wider usage in the United States today. Until recently, economic factors have precluded the use of prestressed concrete in this country, while Europe became the leader in discovering new uses and applications in construction for the material. As new methods are developed in this country, more engineers and contractors are discovering that prestressed concrete is, in many ways, far superior to plain or reinforced concrete. In line with this awakening the Missouri Highway Department is carrying on research to determine the feasibility of prestressed concrete for highway slabs. This study is a part of that research program.

It is the purpose of this study to investigate the shrinkage characteristics of thin prestressed concrete slabs. It has long been known that concrete shrinks as it ages, and it has also been known that under load a further shrinkage takes place. In line with the above research this study will investigate four slabs of concrete, three of which are prestressed, to determine the laboratory shrinkage characteristics. The results of this study will be used to correlate field data.

A REVIEW OF THE LITERATURE

Before launching into the voluminous amount of literature on shrinkage of concrete, it would be wise to define several terms used generally. Shrinkage, plastic flow and creep are terms found throughout discussions and papers on this subject. In this paper, "shrinkage" will be used to define the characteristic volume change in concrete due to drying out. "Shrinkage" occurs, under most circumstances, in all concrete with or without load. It is more difficult to differentiate between "plastic flow" and "creep". In the literature these two terms are used interchangeably. However, in this study, "creep" will be used in preference to "plastic flow". Plastic flow will be used to designate the peculiar characteristic of plastic action in concrete which results in stress adjustments from overstressed areas to adjacent lower stressed areas. Creep will be used to define the long time deformation occurring in concrete under sustained load. This long time deformation is to be distinguished from the elastic deformation occurring immediately when the load is applied. This concept is illustrated in Figure 1, Page 3.

Very likely, the phenomenon of creep in concrete was noticed long before 1907, when Professor W. K. Hatt published the results of a series of deflection tests on concrete beams. This appears to be the first publication available. In his paper, Professor Hatt says: "These results, taken together, show a sort of plasticity in concrete, by which it yields under the action of a load applied for a long time, or applied a number of times"[(1)].

(1) Hatt, W. K., Effect of Time Element in Loading Concrete, Proceedings, A.S.T.M., 1907, p. 421.

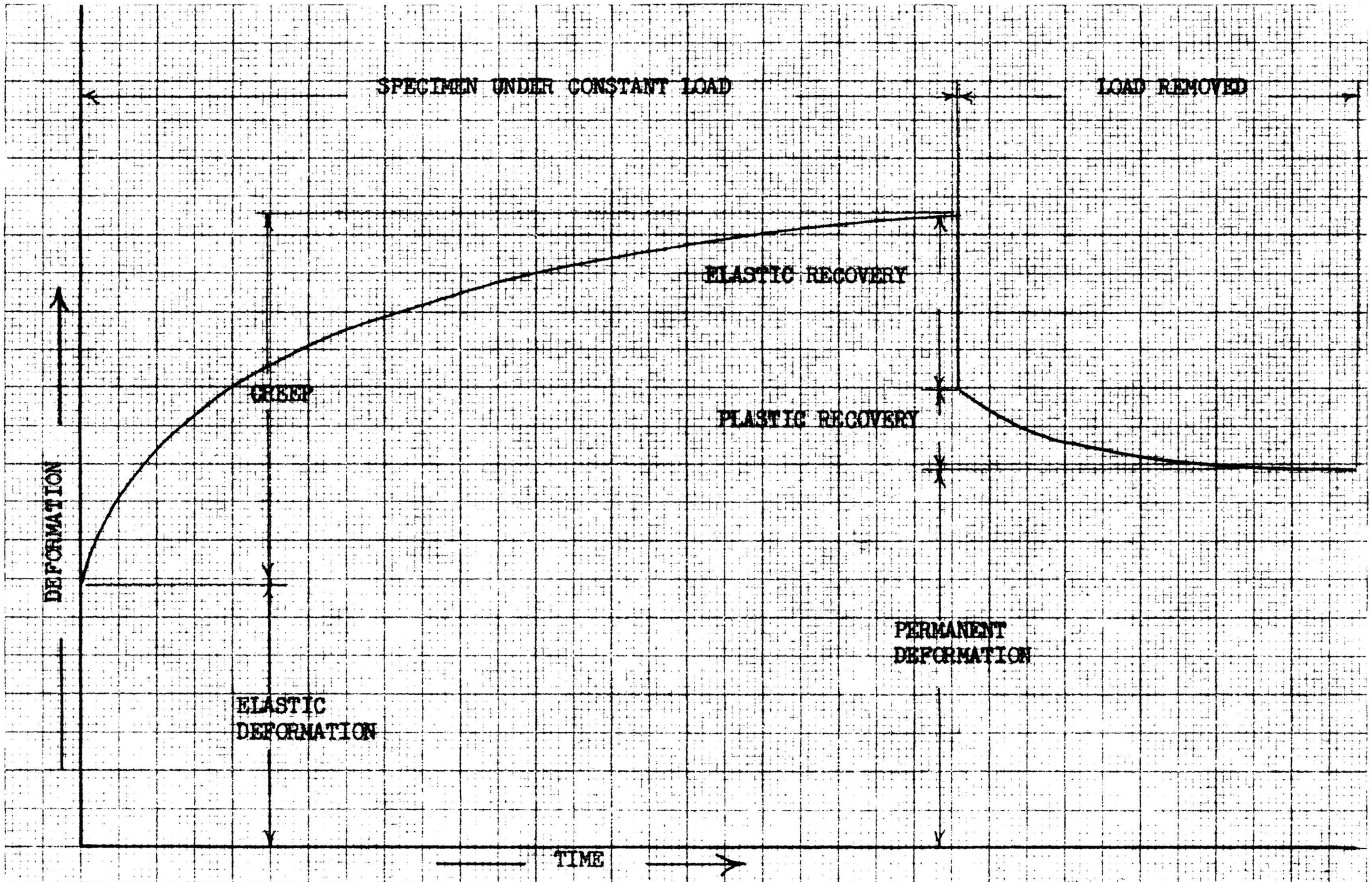


FIGURE 1 - QUALITATIVE ILLUSTRATION OF DEFORMATIONS OCCURRING IN CONCRETE UNDER LOAD

The Hatt, and other early tests, brought about interest in the shrinkage of concrete, both loaded and unloaded. In 1916 a paper was published in the Proceedings of the American Concrete Institute by E. B. Smith of the Bureau of Public Roads in which the author noted that plastic recovery, after a long time sustained load was removed, was considerably less than the plastic flow under the load. This article also showed that concretes under water flow less than those in air[2].

(2) Smith, E. B., The Flow of Concrete under Sustained Load, Proceedings, ACI, Vol. 12, 1916, p. 317.

Also in 1916, a paper was published which noted that the creep, or plastic flow, is rapid at first and undergoes a progressive slowing down as time goes on[3].

(3) Goldbeck, A. T., and Smith, E. B., Tests of Large Reinforced Concrete Slabs, Proceedings, ACI, Vol. 12, 1916, p. 324.

Results of tests conducted at the University of Illinois, and published in 1921, indicate that the shrinkage of concrete is due to a loss of moisture and, hence, a volume change within[4].

(4) Matsumoto, T. A Study of the Effect of Moisture Content upon the Expansion and Contraction of Plain and Reinforced Concrete, Bulletin 126, U. of Ill. Experiment Station, 1921, p. 28.

In 1931, a major contribution to this subject was introduced by Professor R. E. Davis and Mr. H. E. Davis of the University of California. Some of the conclusions arrived at were that: regardless of the character of the concrete or the conditions around it, creep in concrete increases with magnitude of stress and with time; and that, the amount of shrinkage depends on the dryness of the air around it[5].

(5) Davis, R. E. and Davis, H. E., Flow of C ncrete Under Sustained Load, Proceedings, ACI, Vol. 27, 1931, p. 898.

In 1934, the study was expanded by Messrs. Davis, Davis and Hamilton showing the effect of many factors on the shrinkage and creep of concrete. Interesting conclusions which they reached are that the major portion of plastic flow or creep in concrete, under sustained compressive stress, is apparently due to seepage of colloidal water (uncombined) from the cement gel. From this, they found that the water-cement ratio has a marked effect on the amount of shrinkage. Other shrinkages occur from crystalline slippage or flow and from a viscous flow within the concrete structure. They also state that temperature has no effect on shrinkage, but that the moisture content of the air has a marked effect. Finally, in the range from 300 psi to 900 psi, the amount of creep is proportional to the amount of stress[6].

(6) Davis, R. E., Davis, H. E. and Hamilton, J. S., Plastic Flow of Concrete Under Sustained Stress, Proceedings, ASTM, Vol. 34, 1934, p. 383.

The foll wing year Professor J. R. Shank published a paper in which he derived an empirical formula for the creep of concrete under stress with time. This equation is as follows:

$$y = CX^a$$

where:

y = The unit deformation for a unit stress

X = The time in days

C = Coefficient depending on type of concrete and load conditions.

a = Root depending on rate of shrinkage and creep

No attempt was made to separate normal shrinkage from creep. The coefficients in both cases take care of this; for example: a concrete of high water-cement ratio and stored in dry air will have a larger value of "C" because the amount of shrinkage at any time "X" will be greater. The rate of shrinkage depends on these factors also; however, the amount of stress in the concrete is the primary factor. If deformation versus time after loading is plotted on log-log graph paper, a straight line results. The ordinate (deformation) intercept gives the value of "C" while the slope of the curve is the value of the root "a". This equation is significant because in a localized area concrete samples can be tested and shrinkage curves set up for the particular variety of aggregate used under various conditions. These curves can then be used to approximate the amount of shrinkage and creep combined which may be expected over a period of time. The author states that after one year the results of the formula begin to appear too high, and that after five years no more creep should be considered[7].

(7) Shank, J. R., The P astic Flow of Concrete, Ohio State University Engineering Experiment Station, Bulletin No. 91, September 1935.

In 1951 Mr. Robert F. Blanks, Chief of the Research and Geology Division of the Bureau of Reclamation presented a paper to the First United States Conference on Prestressed Concrete at the Massachusetts Institute of Technology. Mr. Blanks's paper contained the effects of various elements on the shrinkage and creep of concrete. In general he states that water-cement ratio, size of cross section and the chemical composition of the cement contribute most to greater drying shrinkage. On the other hand, strength, type and length of curing, amount of load, size and age at loading are factors which will have an effect on the creep of concrete[8].

(8) Blanks, R. F., Concrete for P estressing, Proceedings of the First United States Conference on Prestressed Concrete, M.I.T., 1951, p. 136.

The Concrete Manual published by the U. S. Bureau of Reclamation states that the curve of creep versus time is expressed by a function of the form:

$$\epsilon = \frac{1}{E'} + f(k) \log_e (t + 1)$$

where:

ϵ = total deformation in inches/inch/psi

E' = Immediate elastic modulus upon loading

f (k) = A function representing the rate of creep deformation with time.

The function $\log_e (t + 1)$ indicates that creep continues with time at a diminishing rate with no apparent limit. The function f(k) is large when concrete is loaded at an early age and small when loaded later in its life(9).

(9) U. S. Bureau of Reclamation, Concrete Manual, 1955, p. 25.

In a discussion of a paper, "Theories of Creep in Concrete", by A. M. Neville, Mr. Keith Jones has used the above formula to determine E_s, the modulus of elasticity which is in force while the creep in concrete is taking place. Mr. Jones, an engineer for the U. S. Bureau of Reclamation, expressed his formula as:

$$E_s = \frac{1}{1/E' + f(k) \log_e (t + 1)}$$

Since E is expressed in inches per inch per one p.s.i., and since:

$$\text{(Young's) } E = \frac{\text{STRESS}}{\text{STRAIN}}$$

then E_s is $\frac{1}{\epsilon}$ as above(10).

(10) Jones, K., Discussion of Theories of Creep in Concrete by A. M. Neville, Journal of the ACI, Part II, December 1956, p. 1139.

SUMMARY

Through the literature discussions, the following are listed as the most important factors affecting shrinkage and creep in concrete: moisture conditions, water-cement ratio, strength, load, type of aggregate, type of curing, type of cement, size and age at loading. Since there are so many variables, it is difficult indeed to separate and define any one. One main formula, Shank's[11], exists and will be

(11) Shank, op. cit., p. 2

checked with the results of this study in a subsequent section. Much literature is available, and results in the main are comparable.

MATERIALS

Concrete: The concrete materials were proportioned by weight according to the specified mix set down by the Missouri Highway Department. This mix was as follows:

Item	Parts by Volume
Cement	1
Fine Aggregate	1.97
Coarse Aggregate	3.36
Water (gals./sack)	5.6

The cement used was from single shipments of portland cement. Equal parts of Alpha and Red Ring cement were used. These are type I cements and were carefully screened to remove any parts which may have hardened in storage.

The sand was an approved Pacific, Missouri variety with a specific gravity of about 2.55. The moisture content of the sand was taken the morning of the pour, and this was used to correct the weight of water used.

The coarse aggregate used was a commercial 3/4 inch crushed limestone with a specific gravity of about 2.66, obtained from the Bussen Quarries in Lemay, Missouri. This aggregate was specially crushed for these tests. Moisture content corrections were also run concurrently with those of the sand.

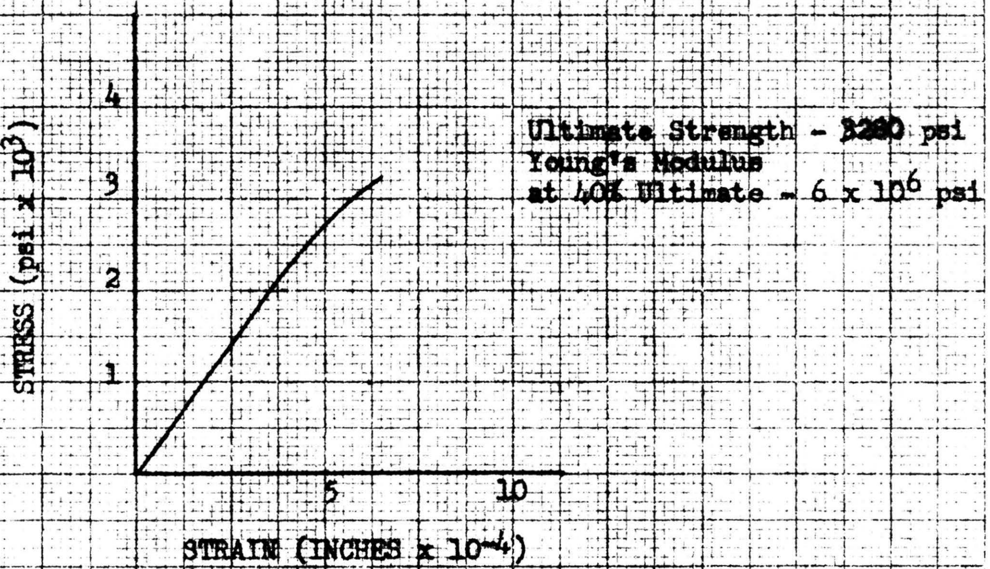
The concrete was mixed in a three cubic foot Lancaster Laboratory Concrete Mixer for at least three minutes. It was necessary to mix two batches per slab. The slump tests made from each batch of concrete averaged from three to three and one half inches, as required by Missouri Highway Department specifications. Three test cylinders, six inches in diameter and twelve inches long, were made from the concrete composing each slab. One of each of the cylinders for each slab was tested at an age of three days (the day prestress was applied), and the remainder were tested at 28 days. The strain was measured with a Compressometer as load was applied. Stress-strain diagrams of the cylinders are shown in Figures 2-9, pp. 12-15. The concrete averaged 4627 psi ultimate strength with a Modulus of Elasticity of 5.7×10^6 psi at 28 days.

Forms: The forms for the slabs were of box construction of 3/4 inch plywood. The bottom was grooved to receive the sides which were bolted and braced in place to preclude any sagging with the weight of the fresh concrete. The entire form was supported off of the floor on six 2 x 2 pieces of lumber along the bottom, to give equal temperature for curing all around the slab. A heavy wax paper was used to line the forms so that no sticking would occur and early removal would be possible without injuring the slabs. The forms were removed very easily after 48 hours, and no spalling occurred. After 14 days the slabs were removed from the plywood platform and placed on one inch lumber slats to insure constant air temperature around the slabs. Two sets of forms were made, and each set was used twice.

Steel: Three sets of steel springs, rods and plates were designed by Mr. B. F. Friberg for applying the prestress to the slabs. The pilot slab (A-1) had no prestress applied, and no steel was used in its construction. The slab numbered A-2 had 100 psi of prestress applied and used three 1 inch steel plates, two 3/4 inch high tension steel rods, and two springs with a spring constant of 4089.6 lbs. per inch. Slab number A-3 (300 psi prestress) used two 1 1/4 inch steel plates, one 1 inch steel plate, two 3/4 inch high tension steel rods and four double spring sets, each with a spring constant of 5731.2 lbs. per inch. Slab number A-4 (500 psi prestress) used two 1 1/4 inch plates, one 1 inch plate, two 7/8 inch high tension steel rods and four double spring sets, each with a spring constant of 12,540.8 lbs. per inch. The rods used were of high tension steel whose modulus of elasticity was 31 x 10^6 psi and whose ultimate strength was 126,000 psi. The springs were purchased from the American Steel Foundries of Chicago, Illinois. The rods were purchased from the L. E. Sauer Machine Company of St. Louis, Missouri.

FIGURE 2

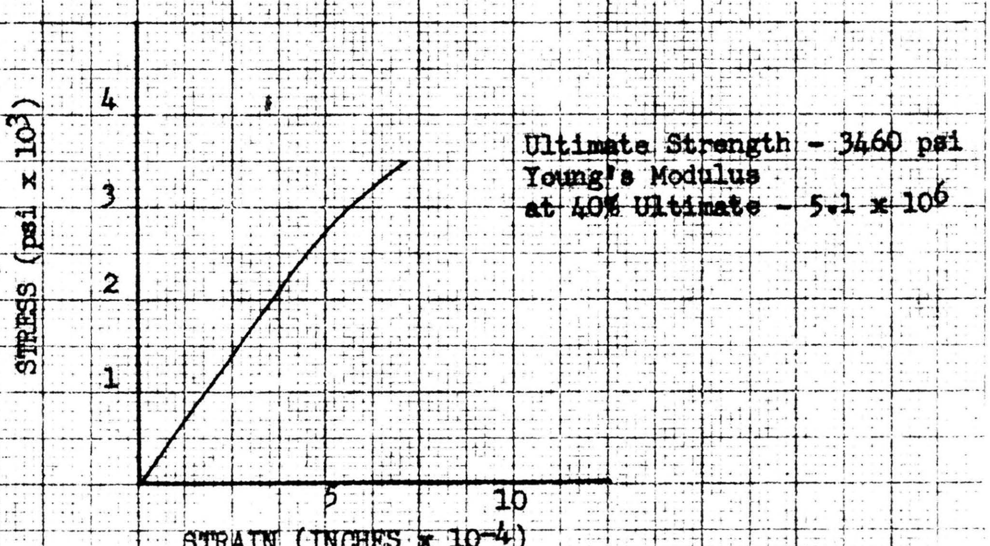
CYLINDER TEST RESULTS



SLAB A-1 (3 DAYS)

FIGURE 3

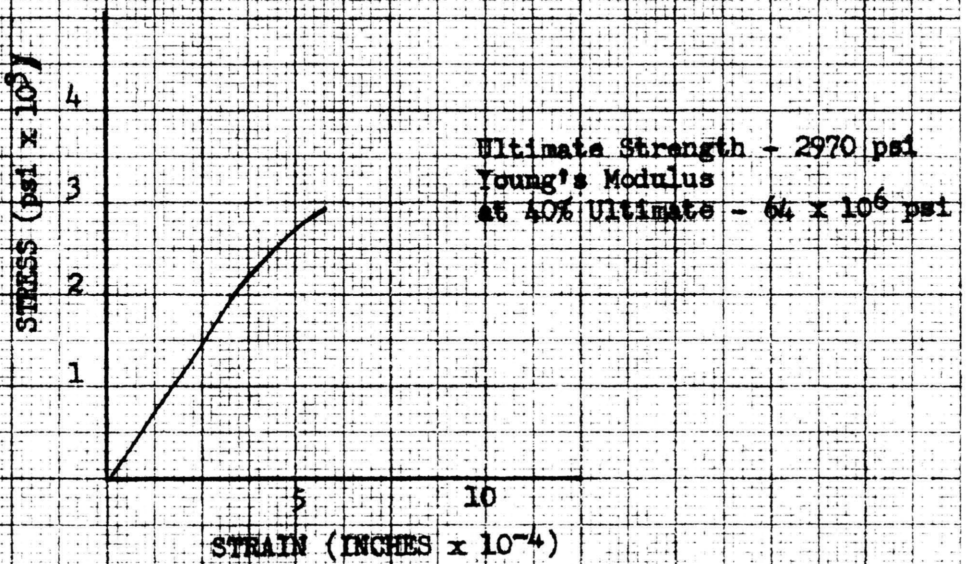
CYLINDER TEST RESULTS



SLAB A-2 (3 DAYS)

FIGURE 4

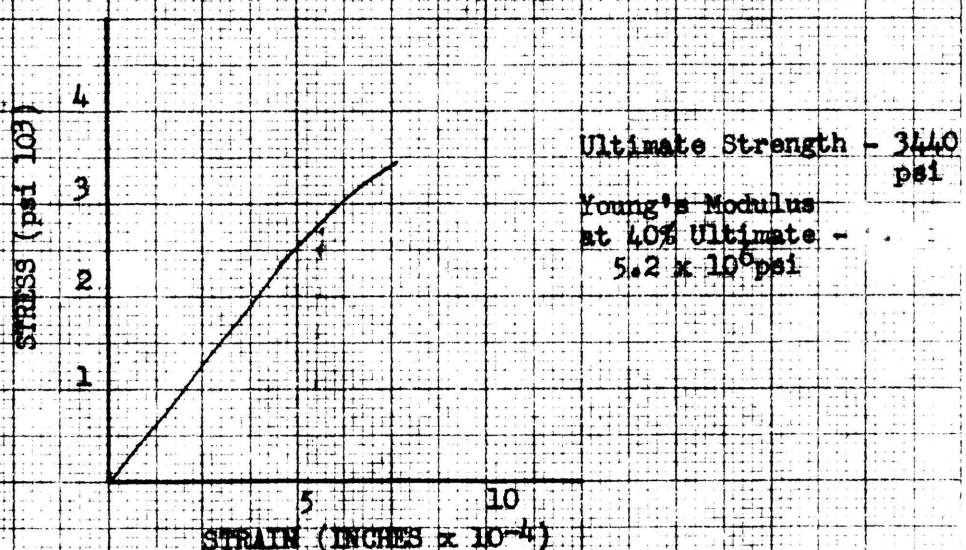
CYLINDER TEST RESULTS



SLAB A-3 (3 DAYS)

FIGURE 5

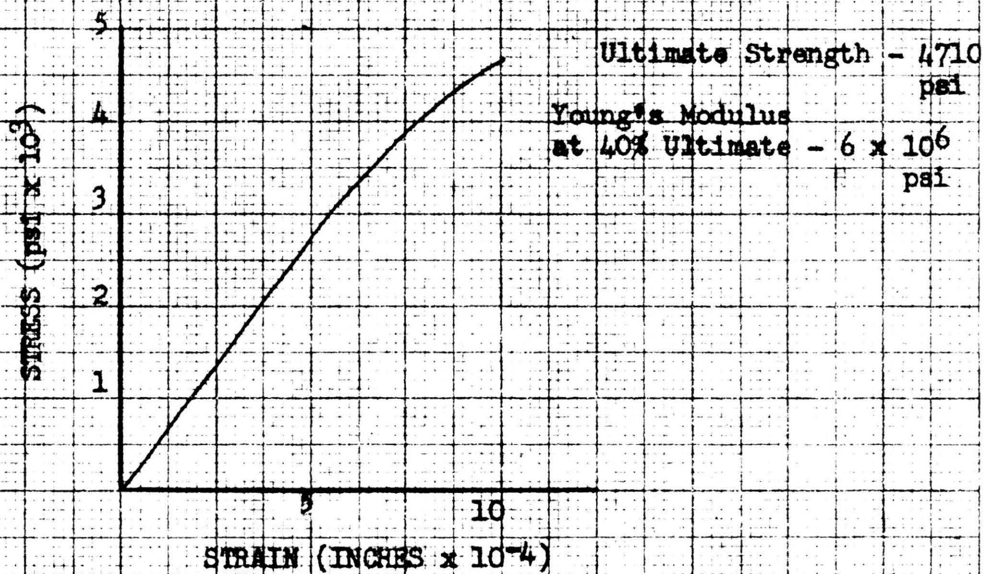
CYLINDER TEST RESULTS



SLAB A-3 (4 DAYS)

FIGURE 6

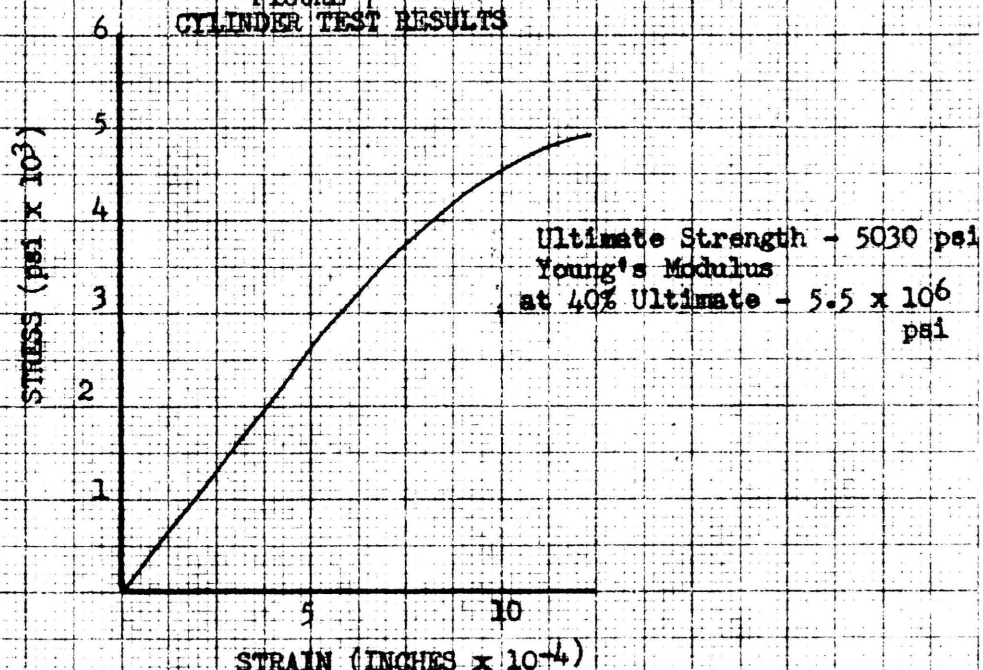
CYLINDER TEST RESULTS



SLAB A-1 (28 DAYS)

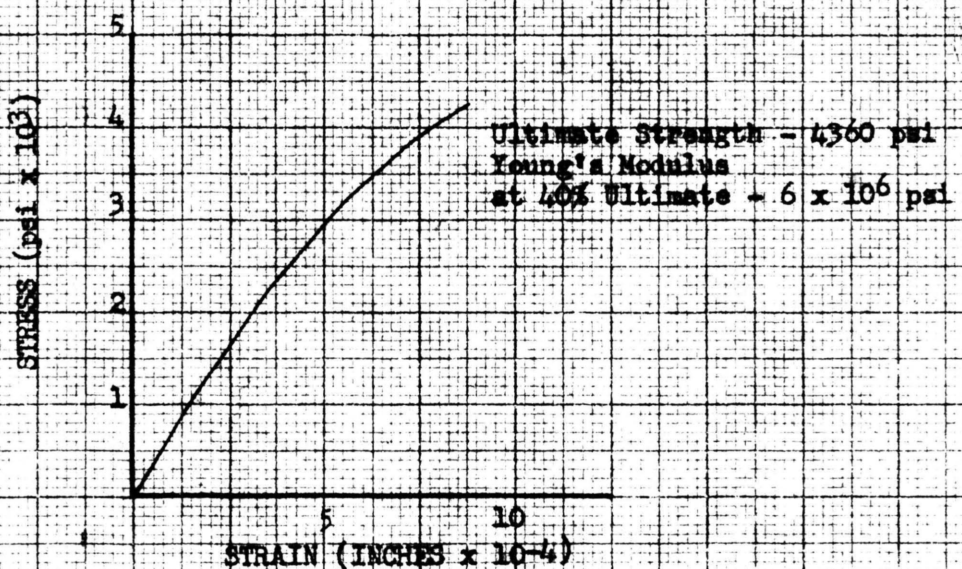
FIGURE 7

CYLINDER TEST RESULTS



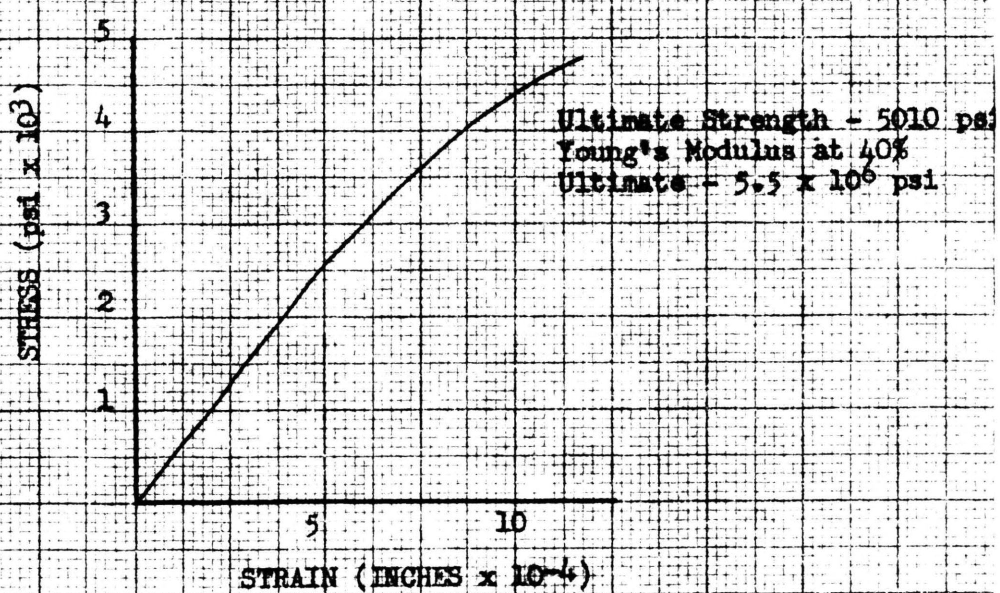
SLAB A-2 (28 DAYS)

FIGURE 8
CYLINDER TEST RESULTS



SLAB A-3 (28 DAYS)

FIGURE 9
CYLINDER TEST RESULTS



SLAB A-4 (28 DAYS)

PROCEDURE AND APPARATUS

Slabs: Four slabs were cast, one to remain unloaded, while the others have 100 psi, 300 psi and 500 psi of prestress applied respectively. The slabs were cast on the second floor of Harris Hall, the Civil Engineering Building on the Missouri School of Mines Campus. The temperature was kept fairly constant, varying only about 15 degrees. The humidity was very constant, varying only about 10% over the entire period of the test. One other point, deserving mention at this time, is the fact that the average humidity was about 33%, very dry for curing concrete.

The slabs themselves were 5 1/2 inches high, 25 inches wide and 54 inches long. (See pictures, plates I through V, pp. 21-24). Temperature wells were cast into each slab in about the middle so that three readings: top, middle and bottom could be taken. Gage plugs were cast into the slab 50 inches apart in the top middle and on the lower part of each side. The post tensioning method of prestressing was used, and it was necessary to cast holes in the concrete by placing 7/8 inch to 1 1/8 inch pipe in the forms. These were withdrawn after the concrete had taken its initial set (about 6-8 hours).

Prestressing: After three days the slabs were post-tensioned to the stresses already mentioned. This was accomplished by jacking the bars until the springs had deformed a given amount. The hydraulic jacks were manufactured by Templeton, Kenly & Company, Broadview, Illinois.

Calculations for the amount of deformation of the springs to provide the desired prestress are as follows:

I. Prestress - 100 psi

Area of plate = 25 (5.5) = 137.5 sq. in.

Bar diameter = 3/4 inch

Bar length = 66.0625 inches

Load necessary = 137.5 (100) = 13,750 lbs.

Load per bar and spring = 13,750/2 = 6875 lbs.

Spring constant (k) = 4089.6 lbs./in.

Total jacking distance = Deformation of spring & elongation of bar

$$DTJ = \frac{P_s}{K} + \frac{P_b l}{AE} = \frac{6875}{40\ 9.6} + \frac{6875\ (66.0625)}{.442 \times 30 \times 10^6}$$

DTJ = 1.7153 in.

Original height of springs - DTJ = Final height of springs

9.0625 - 1.7153 = 7.3472 in.

II. Prestress - 300 psi

Area of plate - 25(5.5) = 137.5 sq. in.

Bar diameter = 3/4 in.

Bar length = 66.5625 in.

Load necessary = 137.5 (300) = 41,250 lbs.

Load per bar = 20,625 lbs.

Load per spring (4) = 10,312.5 lbs.

Spring constant (k) = 5731.2 lbs./in.

Total jacking distance = Deformation of spring & elongation of bar

$$DTJ = \frac{P_s}{K} + \frac{Pol}{AE} = \frac{10.312.5}{5731.2} + \frac{20,625\ (66.5625)}{.442\ (30 \times 10^6)}$$

DTJ = 1.9028 in.

Original height of springs - DTJ = Final height of springs

9.0625 - 1.9028 = 7.1597 in.

III. Prestres- - 500 psi

Area of plate = 25(5.5) = 137.5 sq. in.

Bar diameter = 7/8 in.

Bar length = 65.75 in.

Load necessary = 137.5 (500) = 68,750 lbs.

Load per bar = 34,375 lbs.

Load per spring (4) = 17,187.5 lbs.

Spring constant (k) = 12,540.8 lbs./in.

Total jacking distance = Deformation of spring + elongation of bar

$$DTJ = \frac{P_s}{K} + \frac{P_b L}{AE} = \frac{17,187.5}{12,540.8} + \frac{34,375\ (65.75)}{.601\ (30 \times 10^6)}$$

DTJ = 1.4958 in.

Original height of spring - DTJ = Final height of Spring

$8.25 - 1.4958 = \underline{6.7942}$ in.

The purpose of the springs in the prestressing arrangement is to hold the prestressing force as constant as is possible. The shrinkages obtained are on the order of a few hundreths of an inch. The following example will serve to show the effect of the springs.

I. Prestress = 100 psi

Force per spring set (P_s) = Force per bar (P_b)

Length change of spring + length change of bar = length change due to shrinkage

Shrinkage = 0.0500 in. (more than encountered)

$$\frac{P_s}{K} + \frac{P_b L}{AE} = .05$$

$$\frac{P_s}{4089.6} + \frac{P_s\ (66.0625}{.442\ (30 \times 10^6)} = .05$$

$$(2.45 P_s)\ 10^{-4} + (.0495\ P_s)\ 10^{-4} = 5 \times 10^{-2}$$

$$P_s = 200\#\ \text{change}$$

Prestress change = 200/137.5 = $\underline{1.455}$ psi

Similar calculations for 300 psi and 500 psi slabs give similar results. Since the coefficients of linear expansion due to temperature are very nearly the same for steel and concrete, it can be said that, for all measurable purposes, the prestress remained constant in the slabs.

Readings: The readings taken were: length change, slab temperature, room temperature and room humidity. Readings were taken on the springs also, frequently enough to insure that no majoe slippage had occurred. The length change gage was a 50 inch invar steel, self compensating gage, designed by Mr. Bengt F. Friberg and made by Mr. A. V. Kilpatrick of the Missouri School of Mines. (See Plate V, Page 25). This gage was designed to be self-centering on the brass gage plugs cast into the slabs. Measurements of length change could be read to the one thousandth of an inch and interpolated to the one ten thousandth. Initial readings were taken about 6 to 8 hours after pouring, and all subsequent readings corrected to that as a zero point. Initially, readings were taken on the top and both sides, however, after a short time it was discovered that the gage was to awkward to use on the side readings, so these readings were then only taken periodically, and all were found to agree with the top readings.

Three temperature wells were cast into each slab in the center. One well was 1.5 inches from the top, one in the center and one 1.5 inches from the bottom. In later corrections these three readings were averaged to gain the slab temperature. Weston thermometers ranging from 50° F to 300° F were used to take the temperatures.

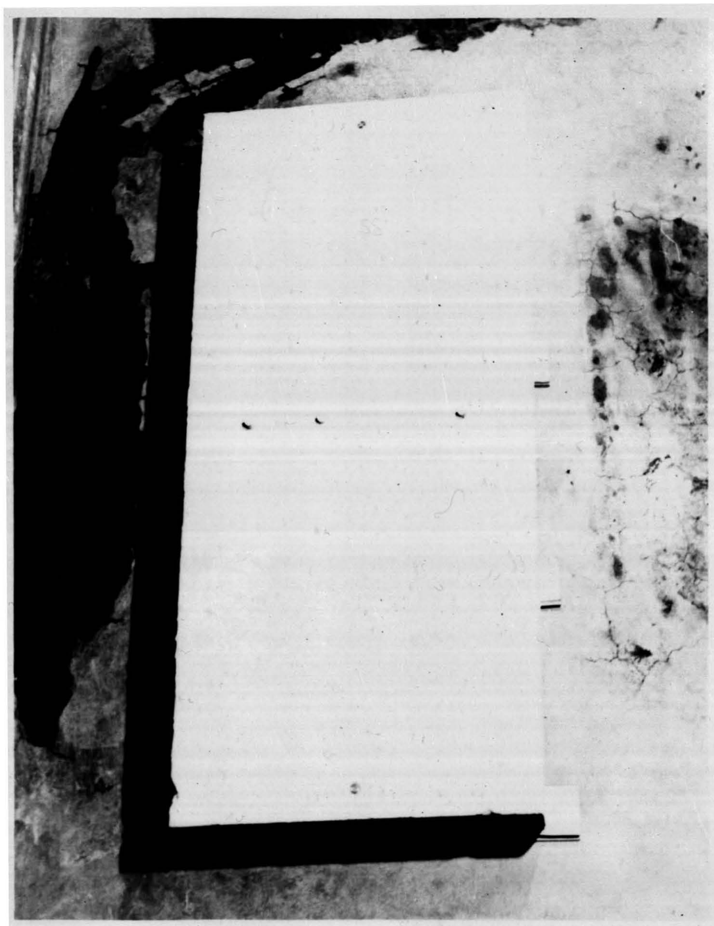
The room temperature was recorded at the time each reading was taken. The thermometer was placed on top of slab A-1 in each case.

Room humidity was taken at each reading with a sling psychrometer. The humidity was very low throughout the period.

Inasmuch as the room temperature did not remain constant, it was necessary to correct the reading so as to remove the factor of temperature swell and shrinkage. In order to do this the temperature was varied from over 90°F to about 60°F over a period of 24 hours. Readings were then taken of the length change, and a value of the coefficient of contraction taken. As the temperature then rose, readings were taken, and these values checked. The results were fairly close to the observed changes. The values used to correct for temperature are given below:

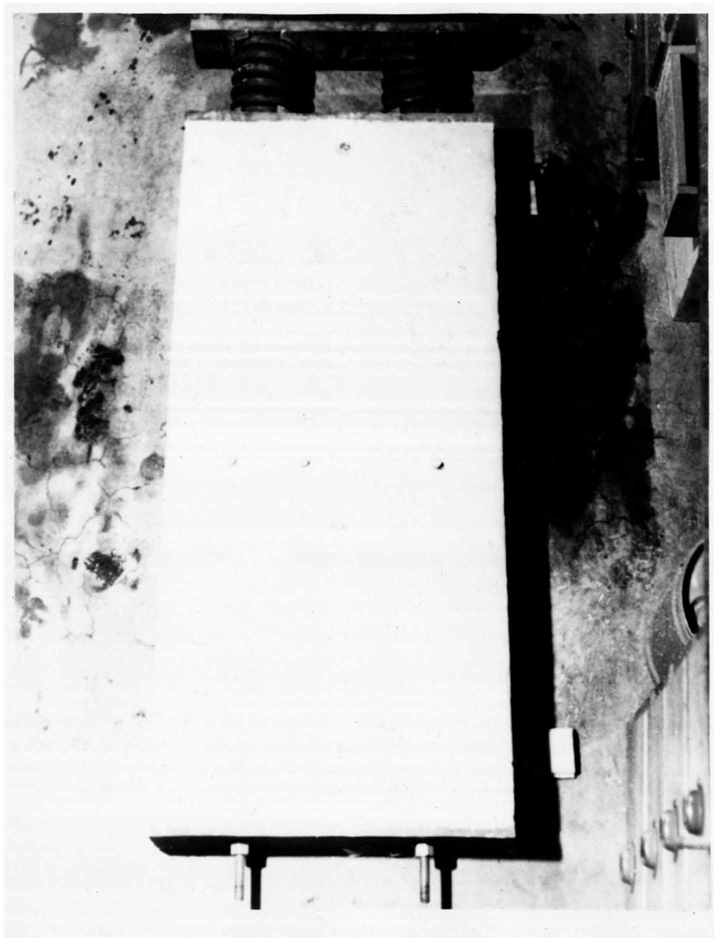
Slab No.	Coefficient (inches/inch/degreeF)
A-1	.00000435
A-2	.00000506
A-3	.00000465
A-4	.00000485

Following now are the results and the discussion of the experiments.



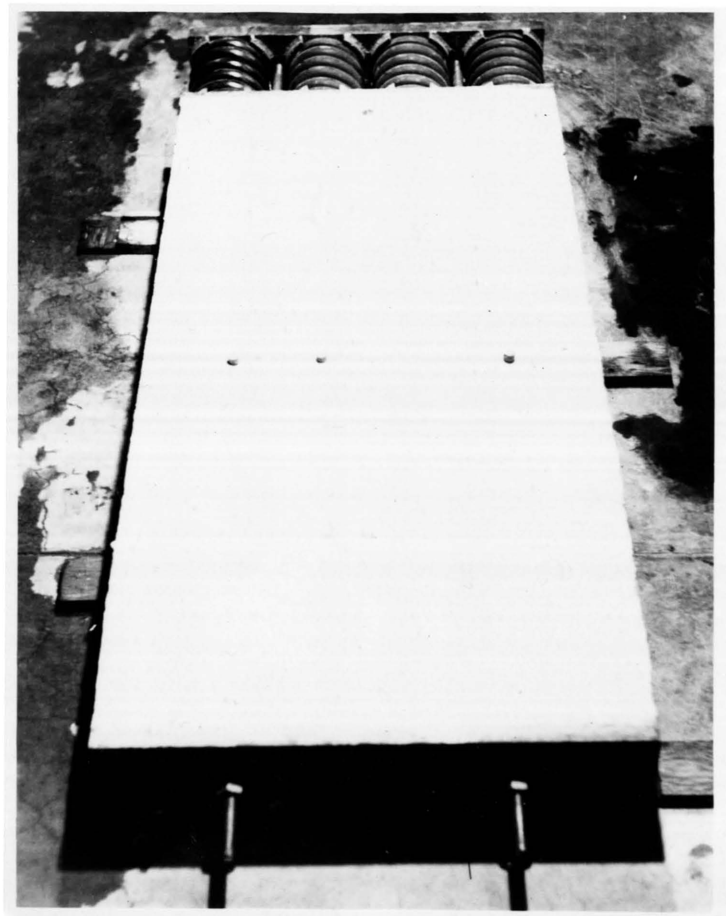
Slab A-1

Plate I



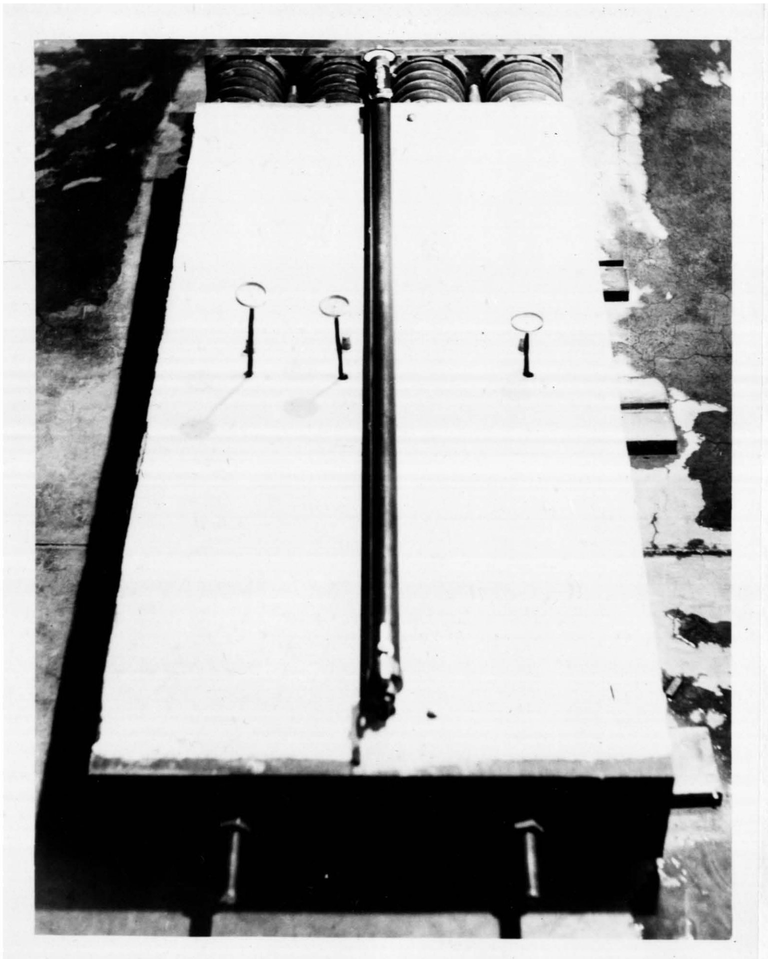
Slab A-2

Plate II



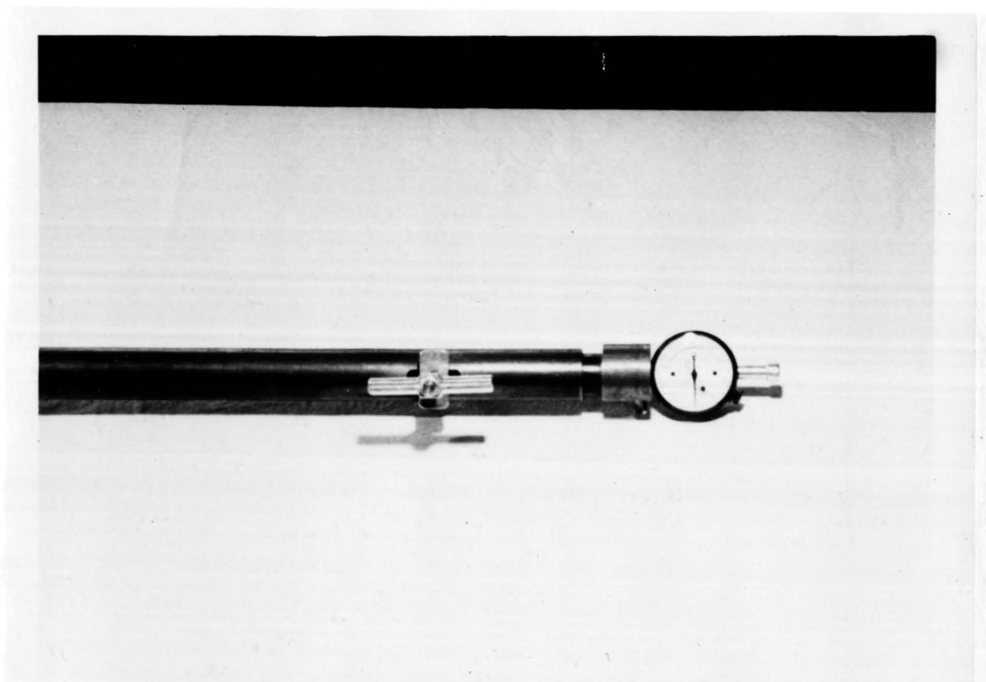
Slab A-3

Plate III



Slab A-4

Plate IV



FIFTY INCH LENGTH CHANGE GAGE

Plate V

RESULTS

Following are the data sheets and the deformation versus time graphs taken for each slab (Tables 1 through 4, Figures 10 through 13). In Figure 14, the graphs are superimposed to show the relative amounts and rates of deformation.

A factor of note is the measured value of Young's Modulus of Elasticity. Each of the cylinders, when tested, determined a three day value, and the slabs, when loaded, showed a deformation from which a three day value may be obtained. The close conformity may be noted below:

Slab	E. Cyl.	E. Slab
A-1	6,000,000	----
A-2	5,100,000	5,000,000
A-3	6,400,000	3,950,000
A-4	5,200,000	5,100,000

The values shown for Slab A-3 may vary conceivably be in error as the ten-thousandth reading is interpolated. An error of .0008 inches would mean an increase in Young's Modulus of 1,000,000. The other values, however, check very closely.

Figure 15 shows the curve of prestress load versus total creep after 100 days. The curve levels off from 100 psi to 0 psi showing that possibly there is little effect on creep for loads less than 100 psi. The curve above 100 psi is a straight line. This concept of creep being proportional to load is in line with conclusions reached by all others who have researched on this topic. Slight variations are, of course, to be expected but, in general, the curve does plot a straight line.

As mentioned before, Mr. Shank has noted that the creep of concrete under load follows a curve of the form:

$$y = CX^{a}$$ (12)

(12) Shank, op. cit., p. 2

In Figures 16 through 18 curves are drawn for the three slabs which were loaded. The curves are drawn on log log graph paper, and the slopes and y - intercepts are noted. The curve,

$$y = CX^{a}$$

takes the form

$$\log y = \log c + a \log x$$

when plotted on this paper. This plot is a straight line where log C is the y - intercept and a is the slope of the line. The equations arrived at are listed below:

Slab	Y-Intercept (c)	Slope (a)	Equation
A-2	2.33	.597	$y = 2.33\ x^{.597}$
A-3	3.07	.363	$y = 3.07\ x^{.363}$
A-4	2.25	.35	$y = 2.25\ x^{.35}$

It can be noted that this curve does not exactly follow the points as shown. One primary reason for this is the early age at which these slabs were loaded. Being very fresh, it is possible that the initial rate of creep was much greater than the test specimens used by Mr. Shank. His specimens were all loaded after at least one month. It appears, however, that after 6-10 days the creep does begin to approximate a straight line. New equations may be calculated ignoring the initial period, and these equations follow very closely the observed creep. These "modified" Shank's Equations are listed below:

Slab	Y - Intercept (c)	Slope (a)	Equation
A-2	3.47	.466	y = 3.47 x .466
A-3	3.62	.312	y = 3.62 x .312
A-4	2.75	.283	y = 2.75 x .283

The values for "C" and "a" found in this research compare very closely with Mr. Shank's work. His value of c for a seven day loading is 2.07, whereas the one determined in this work is 3.07. His value for a is .37, whereas for slab A-3 it is .363. It can be seen that this equation very closely defines the creep curve.

The equations obtained above seem to express the shrinkage of the slabs tested, but there are so many factors which will affect the rate and the total amount of shrinkage and creep in concrete that it cannot be said that all concrete of this mix will deform in the same manner. The main factor determining the values for rate and amount of deformation seems to be the humidity or available water conditions. A specimen stored under water or in a fog cure room would shrink and creep more slowly.

Table 1

Data Sheets

for

Slab A-1 (0 psi Prestress)

Poured 30 November 1956

Cylinder Strength (28 days) - 4710 psi

Young's Modulus of Elasticity - 6×10^6 psi

Thermal coefficient of Expansion - .00000435 in./in./deg. F

SLAB A-1

TIME	ROOM TEMP.	REL. HUM.	SLAB TEMP.	GAGE READING	TEMP. CORR.	CORR. READING
1	78°	36%	83°	0	—	0
2	79°	37%	91°	+8	-17.4	-11.4
3	82°	39%	88.33°	+8	-11.6	-3.6
4	82°	36%	85°	+8	-4.35	+3.7
5	82°	37%	82°	+8	+2.18	+10.2
6	84°	36%	78.67°	-7	+9.4	+2.4
7	84°	36%	78.67°	-9	+9.4	+.4
8	84°	32%	77.67°	-16	+11.6	-4.4
9	85.5°	35%	77.67°	-16	+11.6	-4.4
10	89°	34%	78.33°	-16	+10.10	-5.9
11	89°	33%	78.33°	-16	+10.10	-5.9
12	87°	33%	78°	-17	+10.9	-6.1
13	88°	32%	78.33°	-16	+10.10	-5.9
14	89°	30%	83.33°	-16	-.7	-16.7
15	89°	33%	84.33°	-16	-2.9	-18.9
16	89°	36%	86°	-17	-6.5	-23.5
17	90°	39%	87°	-17	-8.7	-25.7
18	91°	36%	87.67°	-17	-10.10	-37.1
19	91°	35%	88.33°	-17	-11.6	-28.6
20	91°	34%	89°	-17	-13.1	-30.1
21	90°	36%	89°	-18	-13.1	-31.1
22	91.5°	35%	88.67°	-18	-12.3	-30.3
23	90°	36%	88.67°	-20	-12.3	-32.3
24	85°	35%	85°	-35	-4.35	-39.4
25	79°	34%	80°	-47	+6.5	-40.5

SLAB A-1 (Continued)

TIME	ROOM TEMP.	REL. HUM.	SLAB TEMP.	GAGE READING	TEMP. CORR.	CORR. READING
26	81°	35%	81°	+4.35	-2	-43.7
27	81°	35%	81°	+4.35	-1	-44.9
28	81°	35%	81°	+4.35	-3	-47.7
29	81°	33%	81°	-52	+4.35	-47.7
30	82°	30%	82°	-55	+2.18	-52.8
31	83°	29%	82.33°	-55	+1.46	-53.5
32	82°	27%	82°	-53	+2.18	-51.8
33	82°	28%	82°	-58	+2.18	-55.8
34	80°	29%	80.67°	-65	+5.1	-59.9
35	80°	29%	80°	-62	+6.5	-55.5
36	82°	30%	80.67°	-67	+5.1	-61.9
37	85°	36%	83.33°	-63	-.72	-63.7
38	82°	35%	80.67°	-69	+5.1	-63.9
39	86°	35%	85.67°	-66	-5.8	-71.8
40	84°	30%	83.67°	-73	-1.46	-74.5
41	86°	37%	83.67°	-72	-1.46	-73.5
42	87°	37%	85.67°	-72	-5.8	-77.8
43	88°	36%	87°	-71	-8.7	-79.7
44	87°	34%	87°	-72	-8.7	-80.7
45	88°	33%	87.33°	-72	-9.4	-81.4
46	87°	34%	87°	-77	-8.7	-85.7
47	86°	34%	86°	-82	-6.5	-88.5
48	87°	34%	86.33°	-84	-7.2	-91.2
49	88°	35%	88°	-80	-10.9	-90.9

SLAB A-1 (Continued)

TIME	ROOM TEMP.	REL. HUM.	SLAB TEMP.	GAGE READING	TEMP. CORR.	CORR. READING
50	88°	35%	88°	-82	-10.9	-92.9
51	88°	35%	88°	-87	-10.9	-97.9
52	88°	35%	87°	-87	-8.7	-95.7
53	89°	30%	88.67°	-86	-12.4	-98.4
54	85°	30%	85°	-102	-4.35	-106.4
55	85°	30%	84°	-102	-2.18	-104.2
56	86°	33%	86°	-100	-6.5	-106.5
57	87°	33%	87°	-101	-8.7	-109.7
58	86°	33%	86°	-105	-6.5	-111.5
59	87°	40%	86.67°	-103	-8.0	-111.0
60	84°	30%	85°	-111	-4.35	-115.4
61	83°	31%	82.67°	-117	+.72	-116.3
62	79°	30%	80°	-127	+6.5	-120.5
63	78°	31%	79.67°	-129	+7.2	-121.8
64	80°	34%	79.67°	-129	+7.2	-121.8
65	90°	34%	89.33°	-109	-13.8	-122.8
66	83°	33%	85°	-127	-4.35	-131.4
67	81°	35%	81°	-138	+4.35	-133.6
68	86°	35%	87°	-132	-8.7	-140.7
69	88°	30%	88.67°	-139	-12.4	-151.4
70	90°	27%	90.67°	-146	-16.7	-162.7
71	71°	26%	73.67°	-183	+20.3	-162.7
72	58°	31%	64.33°	-207	+40.5	-166.5
73	83°	30%	82.67°	-157	+.72	-156.3
74	94°	25%	95°	-132	-26.1	-158.1

Table 2

Data Sheets

for

Slab A-2 (100 psi Prestress)

Poured 30 November 1956

Cylinder Strength (28 days) - 5030 psi

Young's Modulus of Elasticity - 5.5×10^6 psi

Thermal Coefficient of Expansion - .00000506 in./in./deg. F

SLAB A-2

TIME	ROOM TEMP.	REL. HUM.	SLAB TEMP.	GAGE READING	TEMP. CORR.	CORR. READING
1	78°	36%	81°	0	——	-45.5
2	79°	37%	86°	+18	-12.7	-43.8
3	82°	39%	84.33°	±18	-11.0	-52.1
4	82°	36%	81.33°	+23	-.84	-53.8
5	82°	37%	80°	+8	+1.67	-50.5
6	84°	36%	77.33°	-2	+9.3	-55.5
7	84°	36%	76°	-2	+12.7	-54.2
8	84°	32%	76.67°	-7	+11.0	-52.3
9	85.5°	35%	77°	-7	+10.1	-55
10	89°	34%	77.67°	-7	+8.4	-56.8
11	89°	33%	77.33°	-7	+9.4	-56.2
12	87°	33%	76.67°	0	+11.0	-61.1
13	——	——	76.67°	-10	+11.0	-60.4
14	88°	32%	78.67°	-7	+5.9	-67.6
15	89°	30%	84°	-7	-7.6	-70.5
16	89°	33%	85°	-7	-10.1	-72.2
17	89°	36%	86.67°	-7	-14.4	-74.7
18	90°	39%	87°	-10	-15.2	-74.7
19	91°	36%	88°	-13	-17.7	-77.0
20	91°	35%	88°	-11	-17.7	-75.7
21	91°	34%	89°	-12	-20.3	-81.4
22	90°	36%	89°	-13	-20.3	-90.6
23	91.5°	35%	89.67°	-14	-22.0	-89.7
24	90°	36%	89.33°	-16	-21.1	-85.6

SLAB A-2 (Continued)

TIME	ROOM TEMP.	REL. HUM.	SLAB TEMP.	GAGE READING	TEMP. CORR.	CORR. READING
25	85°	35%	85.67°	-32	-11.8	-43.8
26	79°	34%	81°	-39	0	-39
27	81°	35%	81.33°	-40	-.84	-40.8
28	81°	35%	81°	-41	0	-41
29	81°	35%	82°	-43	-2.53	-45.5
30	85°	33%	81.33°	-43	-.84	-43.8
31	83°	30%	83°	-47	-5.1	-52.1
32	83°	29%	83.67°	-47	-6.8	-53.8
33	82°	27%	82°	-48	-2.53	-50.5
34	82°	28%	82°	-53	-2.53	-55.5
35	80°	29%	80.67°	-55	+.84	-54.2
36	80°	29%	80.33°	-54	+1.7	-52.3
37	82°	30%	81°	-55	0	-55
38	85°	36%	83.67°	-50	-6.8	-56.8
39	82°	35%	80.67°	-57	+.84	-56.2
40	86°	35%	85°	-51	-10.1	-61.1
41	84°	30%	84.33°	-52	-8.4	-60.4
42	86°	37%	84°	-60	-7.6	-67.6
43	87°	37%	86.33°	-57	-13.5	-70.5
44	88°	36%	87°	-57	-15.2	-72.2
45	87°	34%	88°	-57	-17.7	-74.7
46	88°	33%	88°	-57	-17.7	-74.7
47	87°	34%	87.33°	-61	-16.0	-77.0
48	86°	34%	86°	-63	-12.7	-75.7
49	87°	34%	86.67°	-67	-14.4	-81.4

SLAB A-2 (Continued)

TIME	ROOM TEMP.	REL. HUM.	SLAB TEMP.	GAGE READING	TEMP. CORR.	CORR. READING
50	88°	35%	88.33°	-72	-18.6	-90.6
51	88°	35%	88°	-72	-17.7	-89.7
52	88°	35%	88.33°	-67	-18.6	-85.6
53	88°	35%	87.67°	-67	-16.9	-83.9
54	89°	30%	89°	-66	-20.3	-86.3
55	85°	30%	85.67°	-83	-11.8	-94.8
56	85°	30%	84.67°	-83	-9.3	-92.3
57	86°	33%	86.33°	-83	-13.5	-96.5
58	87°	33%	87°	-84	-15.2	-99.2
59	86°	33%	86.33°	-85	-13.5	-98.5
60	87°	40%	87.33°	-83	-16.0	-99
61	84°	30%	85.33°	-88	-11.0	-99
62	83°	31%	82.67°	-93	-4.2	-97.2
63	79°	30%	80.33°	-107	+1.69	-105.3
64	78°	31%	79.67°	-111	+3.4	-107.6
65	80°	34%	80.33°	-113	+1.69	-111.3
66	90°	34%	90.33°	-92	-23.6	-115.6
67	83°	33%	84.33°	-107	-8.4	-115.4
68	81°	35%	81.67°	-117	-1.69	-118.7
69	86°	35%	87.33°	-105	-16.0	-121
70	88°	30%	89.67°	-117	-22.0	-139
71	90°	27%	91°	-119	-25.3	-144.3
72	71°	26%	74°	-162	+17.7	-144.3
73	58°	31%	63°	-182	+45.5	-136.5
74	83°	30%	82.67°	-134	-4.2	-138.2
75	94°	25%	96°	-107	-38.0	-145

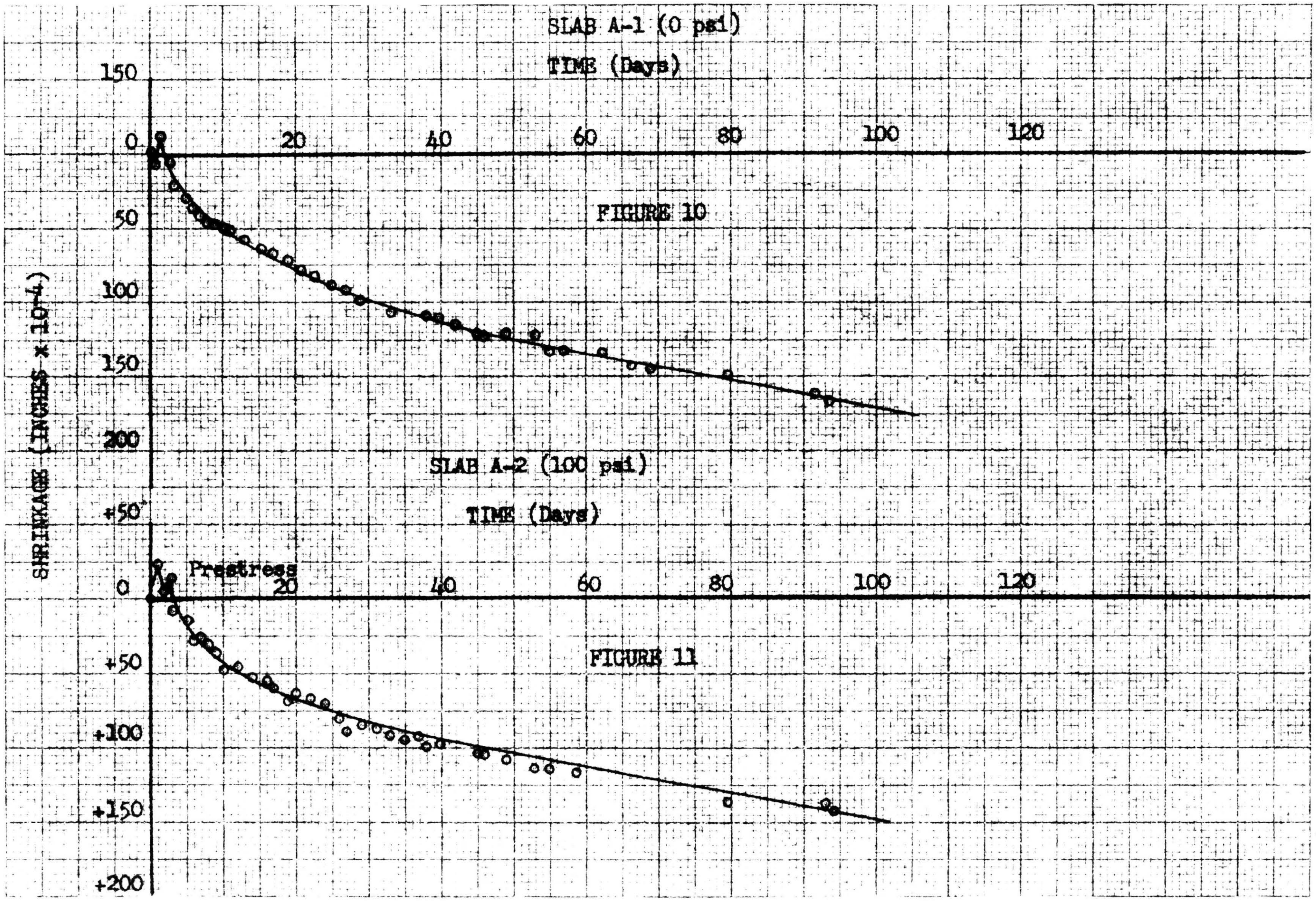

SLAB A-1 (0 psi)
TIME (Days)
FIGURE 10
SLAB A-2 (100 psi)
TIME (Days)
Prestress
FIGURE 11
SHRINKAGE (INCHES x 10^-4)
150
0
50
100
150
200
+50
0
+50
+100
+150
+200
20
40
60
80
100
120

Table 3

Data Sheets

for

Slab A-3 (300 psi Prestress)

Poured 15 December 1956

Cylinder Strength (28 days) - 4360 psi

Young's Modulus of Elasticity - 6 x 10^6 psi

Thermal Coefficient of Expansion - .00000465 in./in./deg. F

SLAB A-3

TIME	ROOM TEMP.	REL. HUM.	SLAB TEMP.	GAGE READING	TEMP. CORR.	CORR. READING
1	83°	34%	92.67°	0	---	0
2	84°	34%	89°	-12	+8.5	-3.5
3	85°	36%	86°	-15	+15.5	+.5
4	83°	35%	84°	-18	+20.2	+2.2
5	81°	35%	80°	-18	+29.4	+11.4
6	78°	36%	79°	-30	+31.8	+1.8
7	82°	35%	74.33°	-30	+42.6	+12.6
8	80°	35%	76°	-29	+38.8	+9.8
9	86°	34%	81.67°	-25	+25.6	+.6
10	86°	35%	81.33°	-21	+19.4	-1.6
11	86°	35%	84.33°	-59	+19.4	-39.6
12	81°	33%	81.67°	-80	+25.6	-54.4
13	84°	30%	83.33°	-85	+21.7	-63.3
14	84°	30%	83°	-87	+22.5	-64.5
15	83°	30%	82.33°	-88	+24.1	-63.9
16	84°	34%	82°	-93	+24.8	-68.2
17	86°	37%	83°	-94	+22.5	-71.5
18	87°	37%	85°	-98	+17.8	-80.2
19	87°	37%	85°	-105	+17.8	-87.2
20	88°	37%	86.67°	-105	+14.0	-91
21	88°	36%	86.67°	-108	+14.0	-94
22	88°	36%	86.67°	-107	+14.0	-93
23	87°	34%	87°	-110	+13.2	-96.8
24	88°	33%	87.33°	-119	+12.4	-106.6

SLAB A-3 (Continued)

TIME	ROOM TEMP.	REL. HUM.	SLAB TEMP.	GAGE READING	TEMP. CORR.	CORR. READING
25	87°	34%	87°	-121	+13.2	-107.8
26	87°	34%	86.33°	-126	+14.7	-111.3
27	86°	34%	86°	-129	+15.5	-113.5
28	87°	34%	86°	-130	+15.5	-114.5
29	88°	35%	88°	-131	+10.9	-120.1
30	88°	35%	88°	-133	+10.9	-122.1
31	88°	35%	87°	-138	+13.2	-124.8
32	88°	35%	86.67°	-140	+14.0	-126
33	89°	30%	88.67°	-145	+9.3	-135.7
34	85°	30%	85°	-160	+17.9	-142.1
35	85°	30%	84°	-164	+20.2	-143.8
36	86°	33%	85.67°	-164	+16.3	-147.7
37	87°	33%	86.69°	-168	+14.0	-154
38	86°	33%	86°	-169	+15.5	-153.5
39	87°	40%	86°	-169	+15.5	-153.5
40	84°	30%	84.33°	-175	+19.4	-155.6
41	83°	31%	82°	-183	+24.8	-158.2
42	79°	30%	79.67°	-197	+30.3	-166.7
43	78°	31%	79°	-200	+31.8	-168.2
44	80°	34%	79.33°	-203	+31.0	-172.0
45	90°	34%	89.67°	-183	+7.0	-176
46	83°	33%	84°	-200	+20.2	-179.8
47	81°	35%	80.33°	-215	+28.7	-186.3
48	86°	35%	86.33°	-217	+14.7	-202.3
49	88°	30%	88.67°	-224	+9.3	-214.7

SLAB A-3 (Continued)

TIME	ROOM TEMP.	REL. HUM.	SLAB TEMP.	GAGE READING	TEMP. CORR.	CORR. READING
50	90°	27%	90.33°	-230	+5.4	-224.6
51	71°	26%	73°	-271	+45.7	-225.3
52	58°	31%	63.33°	-299	+68.1	-230.9
53	83°	30%	82°	-245	+24.8	-220.2
54	94°	25%	96°	-222	-7.7	-229.7

Table 4

Data Sheets

for

Slab A-4 (500 psi Prestress)

Poured 15 December 1956

Cylinder Strength (28 days) - 5010 psi

Young's Modulus of Elasticity - 5.5×10^6 psi

Thermal Coefficient of Expansion - .00000485 in./in./deg. F

SLAB A-4

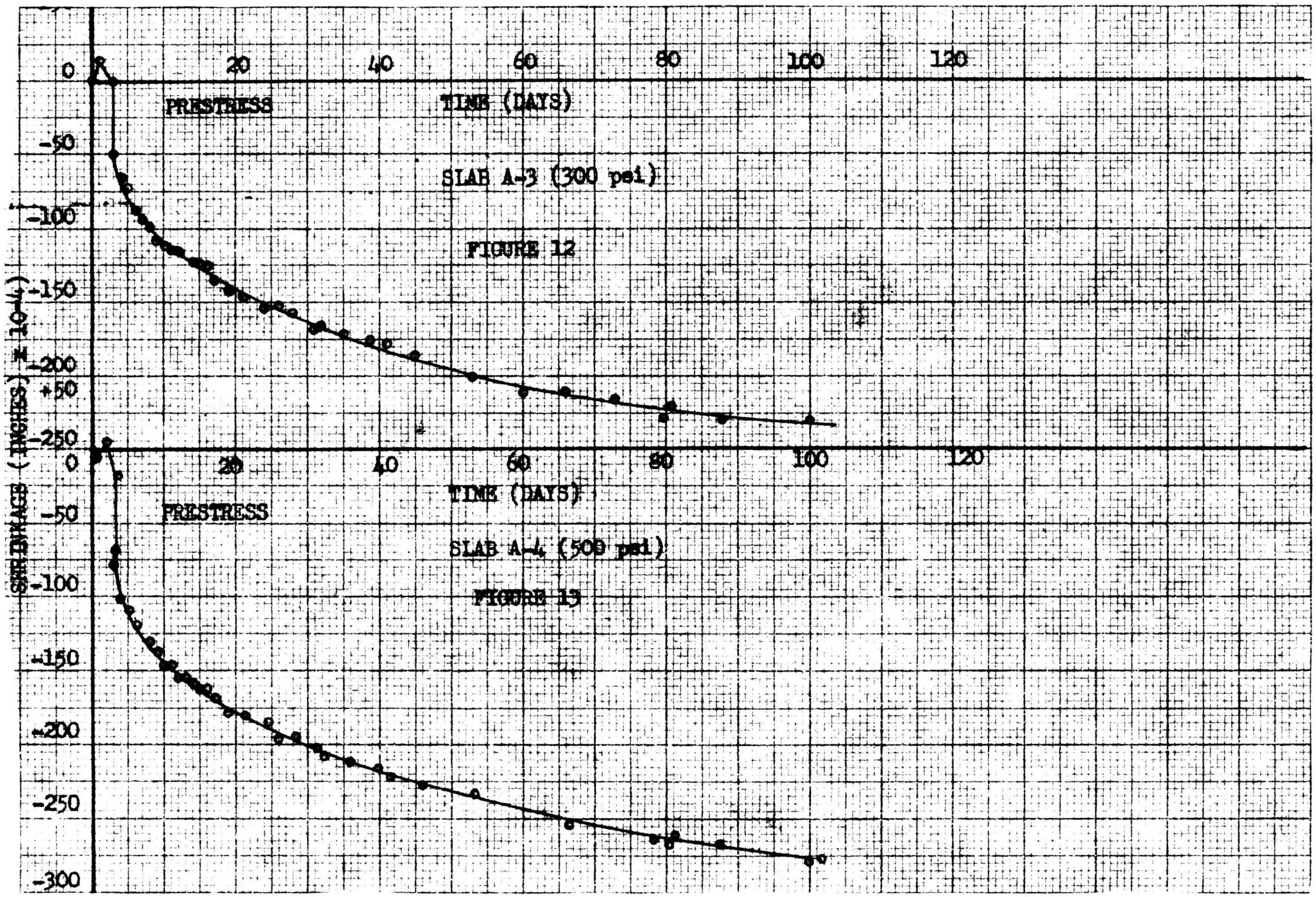
TIME	ROOM TEMP.	REL. HUM.	SLAB TEMP.	GAGE READING	TEMP. CORR.	CORR. READING
1	83°	34%	92.67°	0	——	0
2	84°	34%	90°	-20	+6.5	-13.5
3	85°	36%	86.67°	-16	+14.6	-1.4
4	83°	35%	85.33°	-19	+17.8	-1.2
5	81°	35%	81.33°	-22	+27.5	-5.5
6	78°	36%	79.67°	-56	+31.5	-24.5
7	82°	35%	75°	-41	+42.8	+1.8
8	80°	35%	76°	-39	+40.4	+1.4
9	86°	34%	82°	-36	+25.9	-10.1
10	86°	35%	84.33°	-41	+20.2	-20.8
11	86°	35%	84.33°	-90	+20.2	-69.8
12	81°	33%	82°	-116	+25.9	-90.1
13	84°	30%	83°	-116	+23.5	-92.5
14	84°	30%	83°	-121	+23.5	-97.5
15	83°	30%	82.33°	-126	+25.1	-100.9
16	84°	34%	82°	-130	+25.9	-104.1
17	86°	37%	83°	-130	+23.5	-106.5
18	87°	37%	84.67°	-136	+19.4	-116.6
19	87°	37%	85°	-143	+18.6	-124.4
20	88°	37%	86°	-146	+16.2	-129.8
21	88°	36%	85.33°	-146	+17.8	-128.2
22	88°	36%	86.67°	-145	+14.6	-130.4
23	87°	34%	86°	-148	+16.2	-131.8
24	88°	33%	87°	-153	+13.8	-139.2

SLAB A-4 (Continued)

TIME	ROOM TEMP.	REL. HUM.	SLAB TEMP.	GAGE READING	TEMP. CORR.	CORR. READING
25	87°	34%	87°	-154	+13.8	-140.2
26	87°	34%	86°	-161	-16.2	-144.8
27	86°	34%	85.67°	-165	+17.0	-148
28	87°	34%	86°	-169	+16.2	-152.8
29	88°	35%	87.67°	-170	+12.1	-157.9
30	88°	35%	88°	-174	+11.3	-162.7
31	88°	35%	86.33°	-181	+15.4	-165.6
32	88°	35%	86.67°	-181	+14.6	-166.4
33	89°	30%	88°	-184	+11.3	-172.7
34	85°	30%	85°	-198	+18.6	-179.4
35	85°	30%	84°	-201	+21.1	-179.9
36	86°	33%	85.67°	-201	+17.0	-184
37	87°	33%	86.67°	-204	+14.6	-189.4
38	86°	33%	86.67°	-208	+14.6	-193.4
39	87°	40%	86°	-212	+16.2	-195.8
40	84°	30%	84.33°	-217	+20.2	-196.8
41	83°	31%	82°	-222	+25.9	-196.1
42	79°	30%	79°	-236	+33.1	-202.9
43	78°	31%	78.33°	-242	+34.8	-207.2
44	80°	34%	79.67°	-243	+31.6	-211.4
45	90°	34%	98.67°	-223	+7.3	-215.7
46	83°	33%	83.67°	-243	+21.8	-221.2
47	81°	35%	80.33°	-256	+30.0	-226.0
48	86°	35%	86.33°	-251	+15.4	-235.6

SLAB A-4 (Continued)

TIME	ROOM TEMP.	REL. HUM.	SLAB TEMP.	GAGE READING	TEMP. CORR.	CORR. READING
49	88°	30%	88.33°	-264	+10.5	-253.5
50	90°	27%	90.33°	-269	+5.7	-263.3
51	71°	26%	73.33°	-311	+47.0	-264
52	58°	31%	66.67°	-332	+63.0	-269
53	83°	30%	82°	-288	+25.8	-262.2
54	94°	25%	96.33°	-261	-8.9	-269.9


0
-50
-100
-150
-200
-250
20
40
60
80
100
120
PRESTRESS
TIME (DAYS)
SLAB A-3 (300 psi)
FIGURE 12
SHRINKAGE (INCHES) x 10-4)
+50
0
-50
-100
-150
-200
-250
-300
20
40
60
80
100
120
PRESTRESS
TIME (DAYS)
SLAB A-4 (500 psi)
FIGURE 13

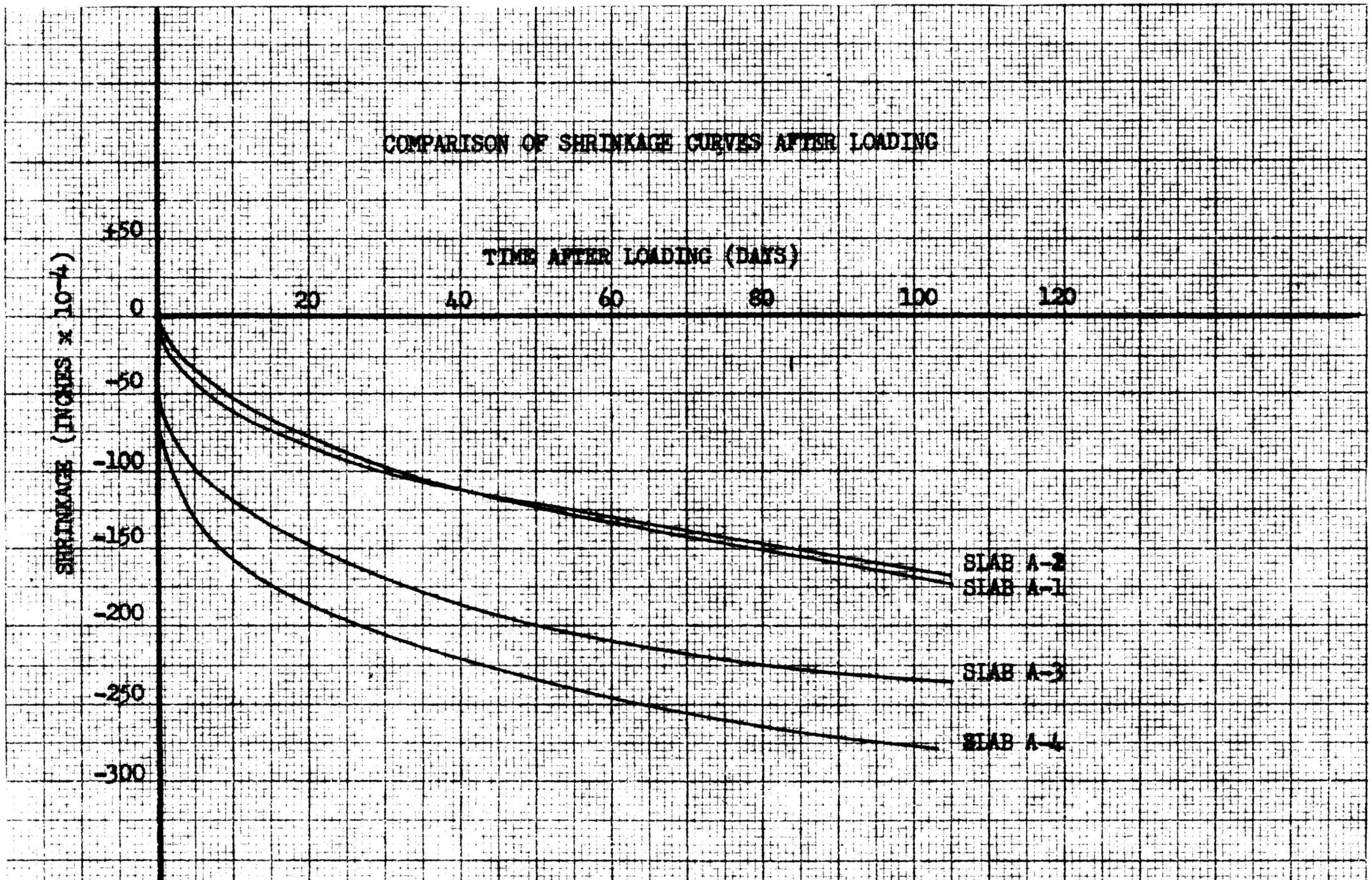

COMPARISON OF SHRINKAGE CURVES AFTER LOADING
TIME AFTER LOADING (DAYS)
SHRINKAGE (INCHES x 10-4)
+50
0
-50
-100
-150
-200
-250
-300
20
40
60
80
100
120
SLAB A-2
SLAB A-1
SLAB A-3
SLAB A-4

FIGURE 14

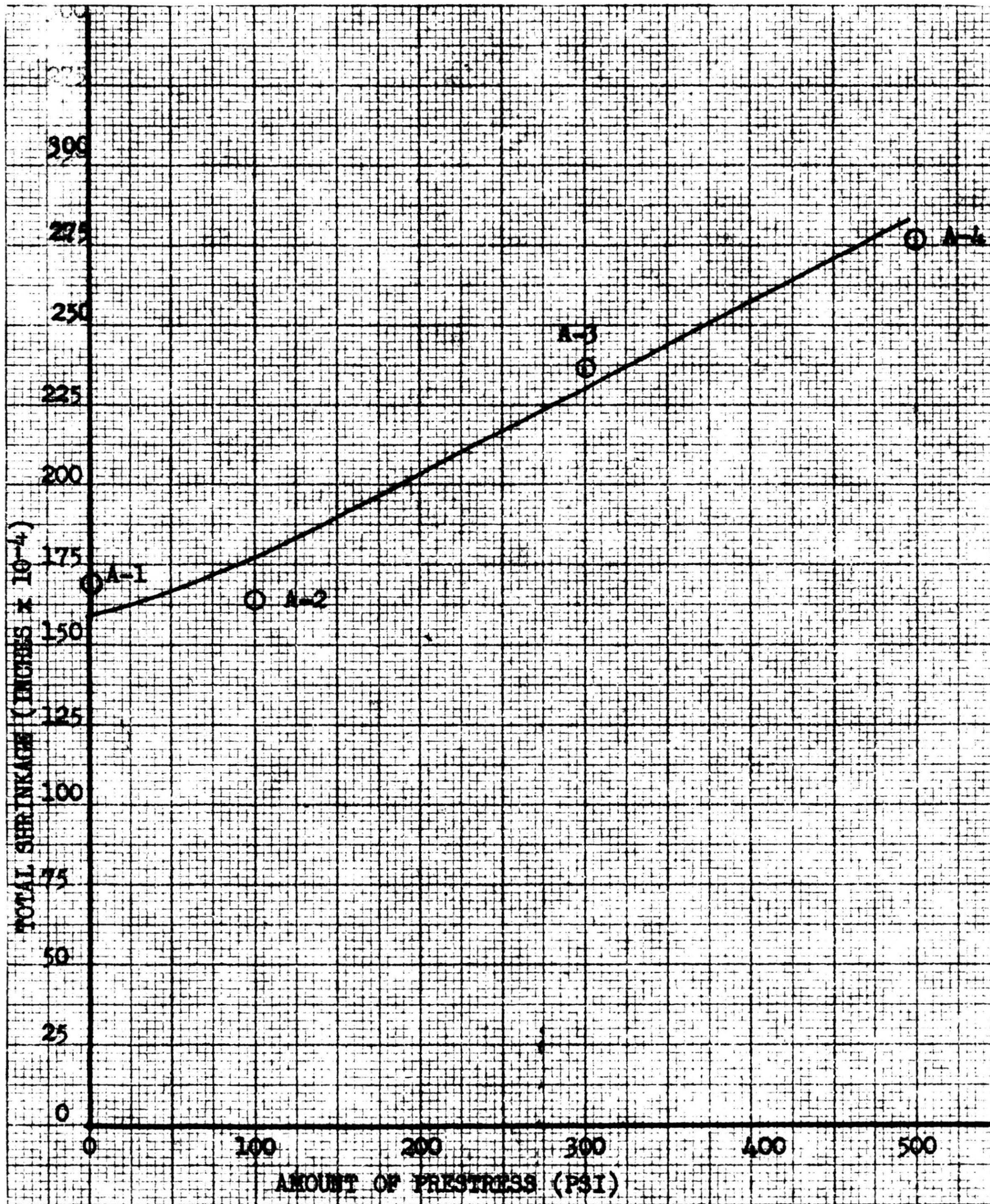
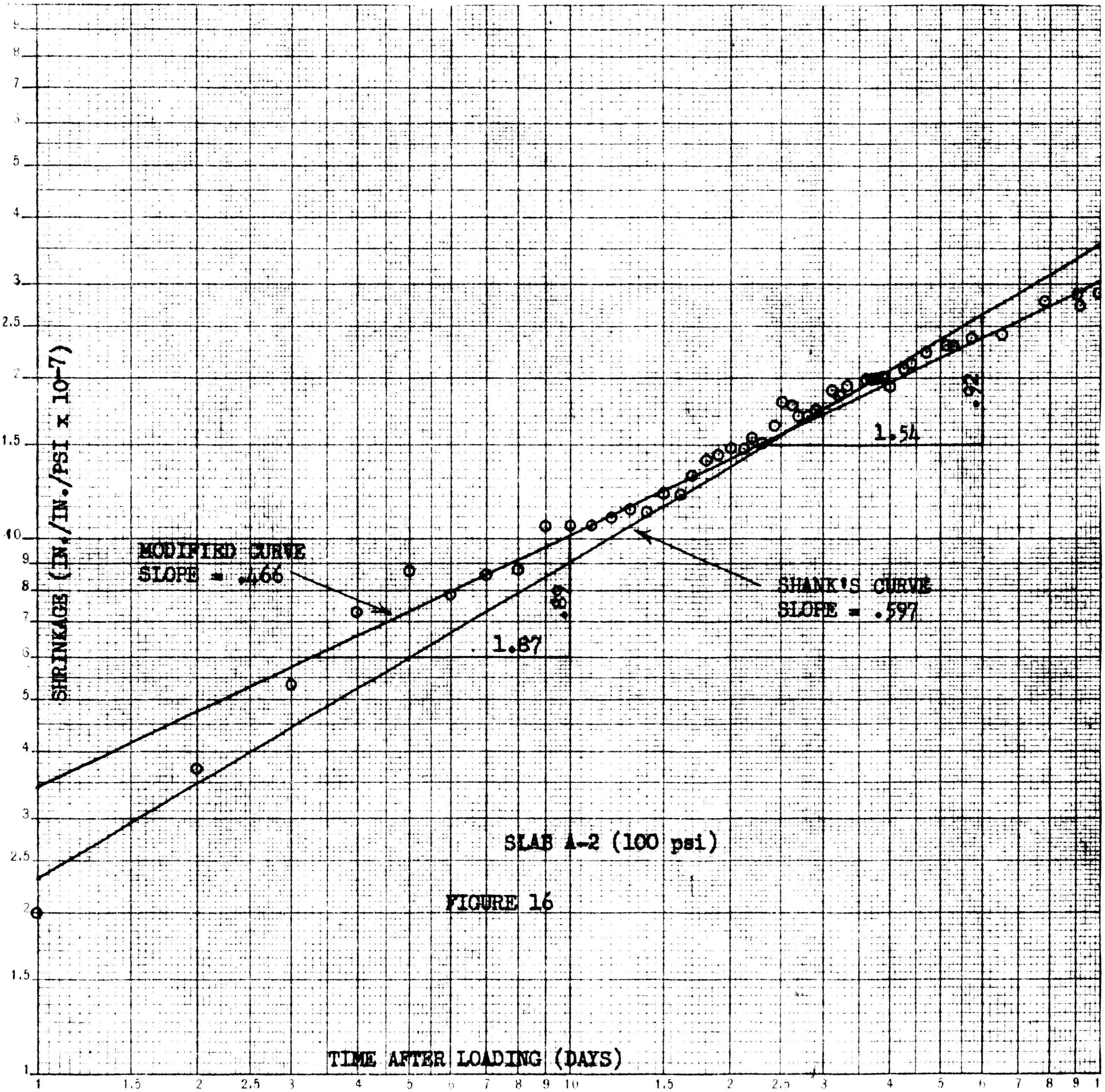


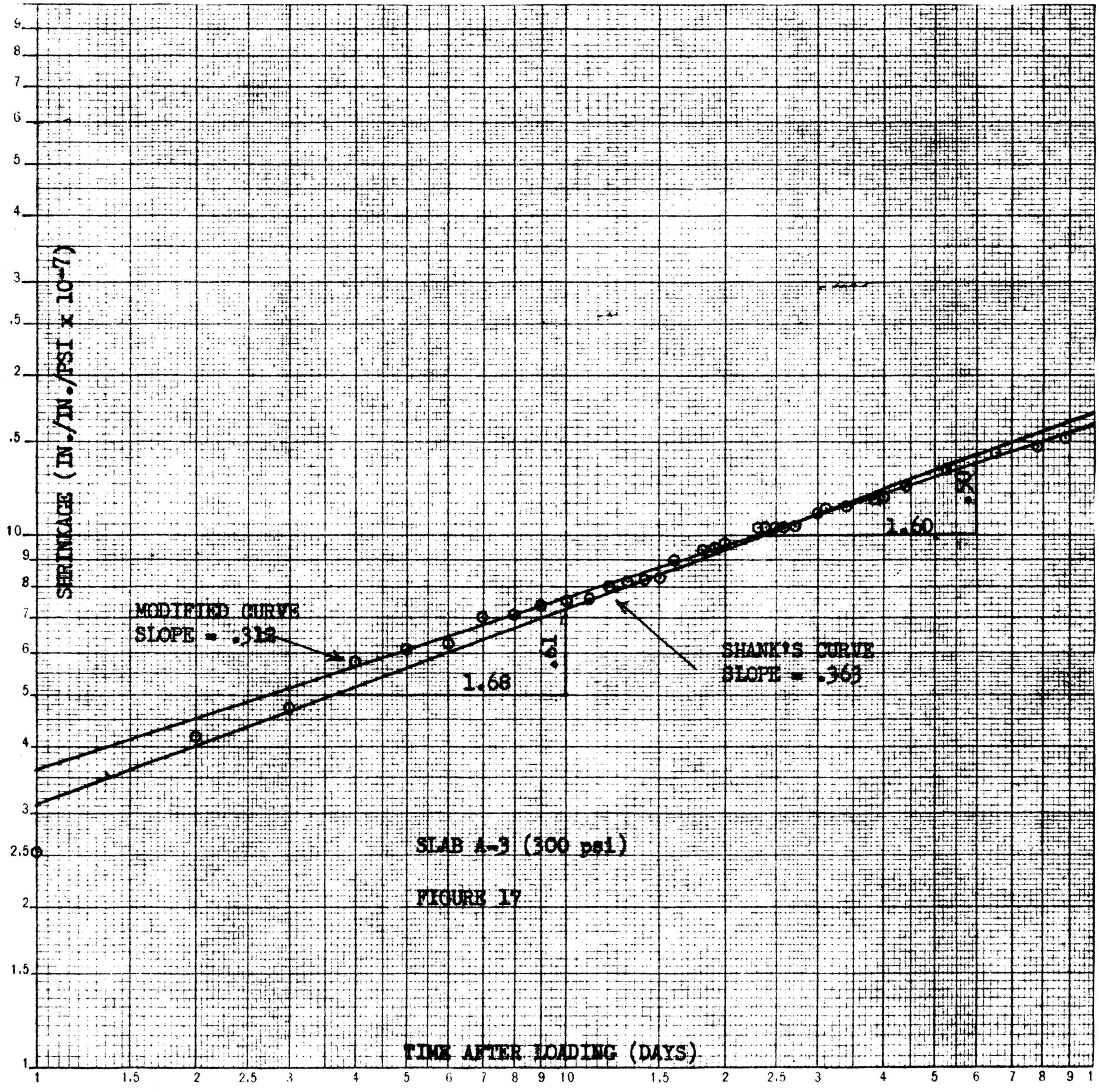
FIGURE 15

VARIATION OF SHRINKAGE WITH PRESTRESS (100 DAYS)



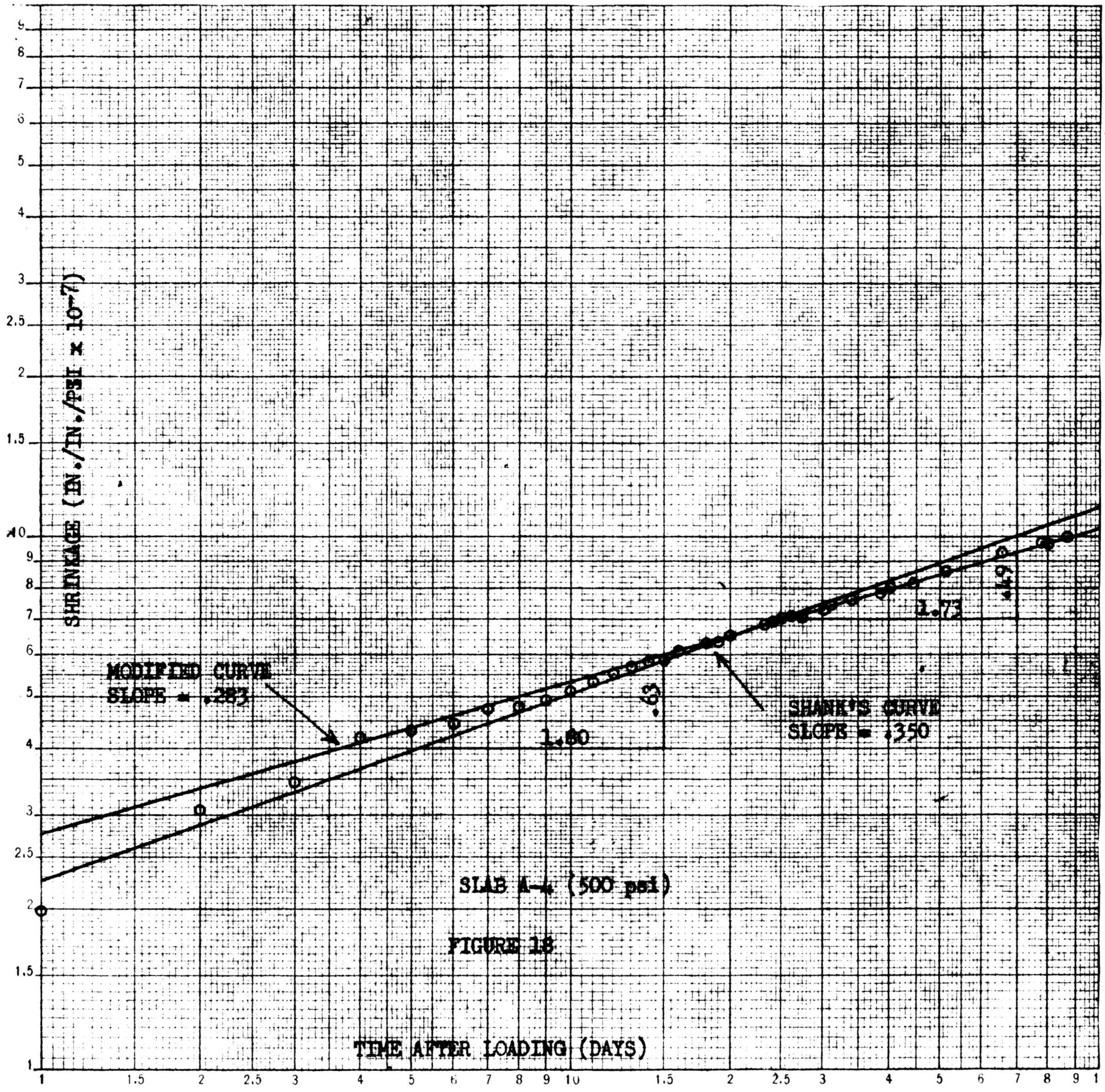
SHRINKAGE (IN./IN./PSI x 10-7)
TIME AFTER LOADING (DAYS)
MODIFIED CURVE
SLOPE = .466
SHANK'S CURVE
SLOPE = .597
1.87
1.54
SLAB A-2 (100 psi)

FIGURE 16



SLAB A-3 (300 psi)

FIGURE 17



SHRINKAGE (IN./IN./PSI x 10^-7)
MODIFIED CURVE
SLOPE = .283
SHANK'S CURVE
SLOPE = .350
1.80
.63
1.73
.49
SLAB A-4 (500 psi)
TIME AFTER LOADING (DAYS)

FIGURE 18

DISCUSSION OF RESULTS

Literature on volume changes in concrete generally conform to theories which indicate that creep in concrete is caused by three separate factors: crystalline slip, in which the crystal structures of the cement gel slide over one another under stress, viscous flow, in which the concrete flows as a very viscous liquid, and water seepage, in which uncombined water is forced out of the concrete very much like the action of a settlement in subsoil under a structure. In a subsoil,water is forced out under the action of a load. This causes a time-consolidation of the soil. In concrete, water is forced from the voids in the same time - consolidation manner decreasing the voids ratio. Experimental results showing increase of creep with increase of humidity around the concrete back up this theory of time-consolidation. To separate the effects of these three is difficult, but their occurrence is in general agreement throughout the literature.

The results of the tests on these pilot slabs indicate that the shrinkage-creep curve for a specimen of concrete is a parabolic function which will plot a straight line on log-log graph paper. This **information**, however, is of little value unless the specimen is tested under very similar conditions to those met in the field. So many factors contribute to the shrinkage of concrete that any prediction as to how much can be expected cannot be made with any high degree of accuracy. However, the "Modified Shanks" curve will give the best result which can be found by this author.

One factor of note is that concrete does creep proportionally with the stress applied. As indicated in Figure 15, Page 48, the curve does not seem to be a straight line below an applied stress of

300 psi. An investigation into the creep of specimens stressed from 0 psi to 300 psi may show that stresses in this region have little or no effect on the creep characteristics of concrete. In line with the accepted theories of crystalline slip, viscous flow and water seepage, stresses of less than 300 psi may not be large enough to cause any major change. This investigation would be valuable because the cost of prestressing at low values would be considerably less if, of course, the same good features of prestressing can be obtained. The creep would not be noticeably increased, and hence there would be less loss of prestress. If the concrete can be kept from cracking at 50 psi and little loss of prestress results, the economic saving would be considerable.

The fifty inch length change gage used had a 90° angle turned on the studs which centered in the plugs cast into the concrete. The inner face of these plugs also were at 90°. It is easy to see that any dirt or dust particles clinging to either surface would throw the readings off. More accuracy would have been gained if the gage stud angle were turned down to something less than 90°. The gage and plug would then contact at only one circumference and dust particles would have little or no effect. Great care was taken that dirt or dust particles had the least effect by taking several readings each time, thereby gaining an average. With the gage as an exception, the only other error introduced was the human error.

CONCLUSIONS

In line with the observed results of this work and the knowledge gained through the experimental results of others in literature, the author has come to the following conclusions concerning the creep characteristics of thin prestressed concrete slabs.

I. (a) The curve defining the shrinkage and creep of concrete under load is best expressed by the equation:

$$y = CX^a$$

(b) This curve is not accurate in the first days when the specimens are loaded at an early age, but is very accurate from 5 to 100 days.

(c) This curve is very similar to the time-consolidation curve of a subsoil settling under the action of a structure load.

II. The creep and shrinkage of concrete under load is proportional to the applied stress except for very low stresses where the effect of the load seems to decrease.

III. The main factors influencing the amount and rate of shrinkage and creep in concrete under load are:

A. Shrinkage (1) Water-cement ratio
(2) Size of cross-section
(3) Moisture conditions

B. Creep (1) Strength of concrete
(2) Amount of load
(3) Age at loading

IV. Minor factors affecting the shrinkage and creep of concrete under load are:

A. Shrinkage (1) Chemical composition of cement

(2) Fineness of cement

(3) Type of aggregate

B. Creep (1) Cement composition

(2) Aggregate

V. Due to the possibility of such wide variance in all these factors, and the inability to separate the effects of any one of them, it is extremely difficult to predict accurately the amount of shrinkage and creep to be expected in a structure. If, however, prior to construction, specimens of concrete made of all the materials to be used can be tested, an equation will be reached which will accurately describe the shrinkage and creep curves. The test specimens must be placed under the same conditions to be expected in the final structure for the derived equation to be accurate.

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VITA

Wayne F. Alch was born on July 13, 1931, in St. Louis, Missouri, the son of Mr. & Mrs. E. Walter Alch.

His early education was received in St. Louis County, Missouri. He entered Culver Military Academy, Culver, Indiana in 1945 and graduated in 1949. From there he received an appointment to the United States Military Academy, West Point, New York. He graduated in 1953 and was commissioned as a Second Lieutenant of the United States Army Corps of Engineers. After attending the Engineer Officers Basic Course at Fort Belvoir, Virginia from August to November, 1953, he spent sixteen months in construction work in Korea. He returned in 1955 and in June, 1956, entered the Missouri School of Mines and Metallurgy under the Army Civil Schooling Plan for Regular Army Officers.

He was married in June, 1955 to Mary Anne Geraghty, daughter of Mr. & Mrs. Howard J. Geraghty of St. Louis, Missouri.

In January, 1957, his son, Brian G. Alch, was born in Rolla, Missouri.